# Dynamical Dark Energy with Dark Sector Interactions: A Combined Fluid Approach to the Hubble Tension

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## State of the art

Measurements of the CMB and Large-scale structures (LSS) are used to test model validity.[1]

### Hubble Tension

The model is adjusted as improved measurements of the SNeIa and CMB produced a 5σ disagreement in the early-time and late-time Hubble constant $H_0$[1,2].

### The Dark Energy Spectroscopic Instrument (DESI)

Measuring baryon acoustic oscillations across $0.3 < z < 2.3$, has in its DR2 release shown a preference for *dynamical* dark energy, an equation of state that evolves with time, over a cosmological constant. We ask whether dark-sector interactions can accommodate this preference while easing the Hubble tension.[3]

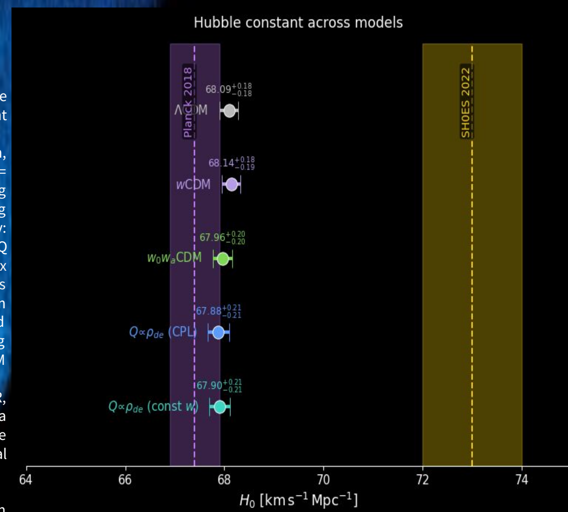
## Methodology

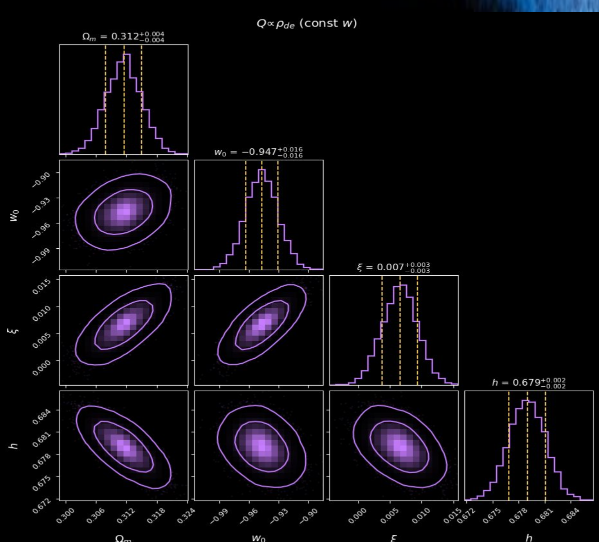
We perform a background-level analysis, solving the modified expansion history and sampling the joint posterior via MCMC.

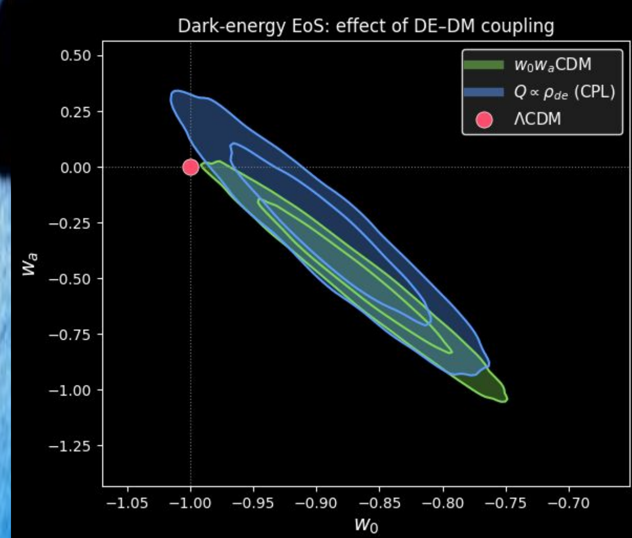
We model dark energy with the CPL parametrization, $w(a) = w_0 + w_a(1-a)$, reducing to ΛCDM when $(w_0, w_a) = (-1, 0)$. Interactions are introduced through a coupling term Q in the dark-sector continuity equations, allowing energy to flow between dark matter and dark energy: $\dot\rho\_dm = -3H\rho\_dm + Q$ and $\dot\rho\_de = -3H(1+w)\rho\_de - Q$ [4,5]. We test three phenomenological forms, $Q = 3H\xi\rho\_x$ for $x \in$ {de, dm, de+dm}, where ξ is a dimensionless coupling (ξ = 0 recovers the uncoupled case). Every form is run against both the dynamical ($w_0w_a$) background and a constant equation of state, giving six interacting models compared against ΛCDM, wCDM, and $w_0w_a$CDM baselines.

Likelihoods combine Planck 2018 CMB distance priors (R, ℓ_A, $\Omega\_b h^2$), DESI DR2 BAO, and the Pantheon+ Type Ia supernova compilation, with the supernova absolute magnitude analytically marginalised so the local distance scale is set by BAO+CMB. [6,7]

Constraints on ($w_0$, $w_a$, ξ, Ω_m, $H_0$) are derived for each model.




## Fluid models

In the standard model, each cosmic fluid, radiation, baryons, cold dark matter (CDM), and dark energy (DE), conserves its energy density independently as the Universe expands. *Interacting* dark-sector models relax this: CDM and DE are allowed to exchange energy through an interaction kernel Q, while their combined density stays conserved. The continuity equations become

$$\dot\rho\_dm + 3H\rho\_dm = Q \quad (1)$$

$$\dot\rho\_de + 3H(1+w)\rho\_de = -Q \quad (2)$$

so Q sets the direction and rate of energy flow between the two sectors. *Phenomenological* models choose Q from physical reasoning and fit it to data, rather than deriving it from a specific particle or field, a flexible, model-independent way to test whether the dark sector deviates from ΛCDM. [1]

## Results

The dynamical-dark-energy preference is reproduced: $w_0w_a$CDM yields $w_0 = -0.87 \pm 0.05$ and $w_a = -0.50 \pm 0.22$, departing from ΛCDM with $w_a$ deviating at ~2σ, consistent with DESI DR2. The coupling is mild and parameterization-dependent. ξ is consistent with zero under CPL (ξ = 0.004 ± 0.003) but sharpens to ~2.4σ for constant w (ξ = 0.007 ± 0.003), reflecting a $w_a$–ξ degeneracy. Critically, all models return $H_0 \approx 68$, none reaching the local value: neither dynamical dark energy nor the viable coupling resolves the Hubble tension under sound-horizon calibration. We further find that only the dark-energy-proportional coupling is stable at background level; both ρ_dm-scaled forms develop an early-time instability (ρ_de driven negative at high z) and are deferred to a full perturbation-level treatment.

## Future steps

A full Boltzmann (perturbation-level) treatment with CLASS or CAMB is the planned next step. This enables the complete Planck likelihood rather than compressed priors, allowing the four deferred models to be assessed at perturbation level, and unlocks growth-of-structure observables that extends the analysis to the $S_8$ tension. Runs like that require high-performance computing (Clusters) for the expanded parameter space.

### References

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